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TITLE: ELECTROMAGNETIC ENERGY APPLIED TO AND GAINED FROM LUNAR MATERIALS

AUTHOR(S): T. T. Meek, D. T. Vaniman, R. D. Blake, and F. H. Cocks

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ELECTROMAGNETIC ENERGY APPLIED TO AND GAINED FROM LUNAR MATERIALS

T. T. Meek, D. T. Vaniman, R. D. Blake, and F. H. Cocks[1]
Materials Science & Technology Div. & Earth and Space Sciences Div.
Los Alamos National Laboratory
Los Alamos, NM 87545 USA

ABSTRACT

Electromagnetic energy may be useful in microwave frequencies for in-situ melting or sintering of lunar regolith. Simple configurations of magnetron or gyrotron tubes might be constructed for unique melting geometries. For energy production, lunar ilmenite has potential applications in photovoltaic devices.

I. Introduction

Lunar materials can be used to fabricate products for use in space. The launch costs in lifting materials from Earth require that extensive development projects in space use lunar materials if those projects are to be economical. This paper explores two directions in the possible impact of lunar materials for adaptation of microwave energy systems to the near-Moon space environment. One direction leads to the possible uses of fused or sintered lunar regolith in the formation of structural forms, particularly in situations where material must be fused in situ. The other direction is toward the use of lunar ilmenite as solar cells for solar-electric energy production. The following discussion addresses in general terms how lunar regolith might couple with microwave radiation and how the products of such coupling might be used. Finally, the results of initial experiments with Schottky-barrier solar cells made from terrestrial and simulated lunar ilmenite are compared.

II. Heating of Lunar Regolith by Microwave Energy

In order to determine how well lunar materials would couple to 2.45 GHz microwave radiation, several different terrestrial materials with properties somewhat similar to lunar materials have already been heated. These simulant materials include an ilmenite rich feldspathic rock [1,2] and a simulated glassy high-titanium lunar regolith made from reagent-grade chemicals [3]. The results obtained from these experiments support the conclusion that mobile defects in lunar materials will affect the loss tangent and increase the coupling of such materials to 2.45 GHz microwave radiation. Early work by Lark-Horovitz [4] showed that defects introduced into Fe_2O_3 by addition of small amounts (less than one atom percent) of TiO_2 can reduce the resistivity of hematite by eight orders of magnitude. This resistivity drop results in correspondingly improved coupling and more rapid sintering of hematite at 2.45 GHz [2]. Typical lunar regolith material might be expected to have a resistivity quite high (10^{13} ohm-centimeter) and might therefore be expected to couple poorly to microwave energy unless very strong electric fields were employed. However, since this material has approximately 10^{6} fossil cosmic ray or solar wind traces per cubic centimeter it should couple extremely well if these defects are mobile. Added to the fossil traces are shock-induced crystal defects that result from the intense impact history of the lunar regolith, as well as surface-correlated volatile materials such as hydrogen and helium. These combined features have the potential of making the loss tangent of lunar regolith extremely propitious for microwave heating.

In attempting to model how well the lunar regolith will heat in a weak 2.45 GHz environment the following expressions were used. First, the power coupled into the material per unit volume was calculated:

1) $P = Kfe^2 \varepsilon'/_{\varepsilon o} \tan\delta$ watts/cm^3

where P is power per cubic centimeter, K is a constant, 55×10^{-14}, E is electric field intensity in volts/cm, tan δ is the loss tangent, $\varepsilon'/_{\varepsilon o}$ is the relative dielectric constant k'.

Values of P were calculated using approximate values for k' and tan δ and converted to calories per cubic centimeter. These values will probably vary considerably over the lunar surface. The range of k' assumed was 2=k'=5 and the values chosen for tan δ (0.015 - 0.3) follow conservative assumptions based on electrical data for lunar samples [5,6,7,8,]. All data calculated for this paper are conservative, and the initial heating experiments indicate that coupling will occur much more rapidly than we report. Shown in figures 1-3 are calculated power density curves as a function of electric field intensity, dielectric constant, and temperature. Figure 4 shows tan δ vs temperature data used.

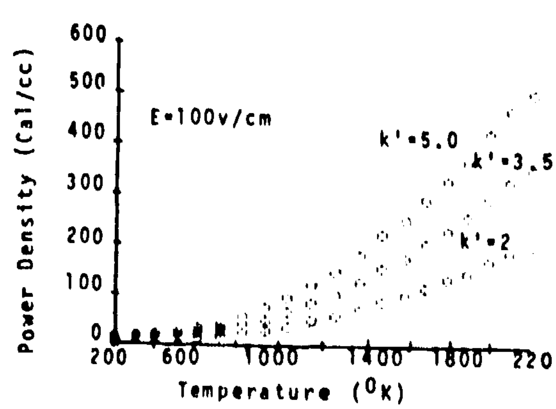

Figure 1. Calculated power density vs temperature coupled into lunar regolith using 2.45 GHz electromagnetic radiation with E=100v/cm and various values of k'.

[1]Mechanical Engineering Dept., Duke University, Durham, NC.

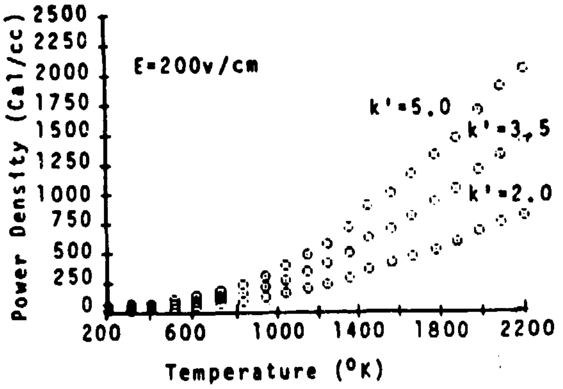

Figure 2. Calculated power density vs temperature coupled into lunar regolith using 2.45 GHz electromagnetic radiation with E=200v/cm and various values of k'.

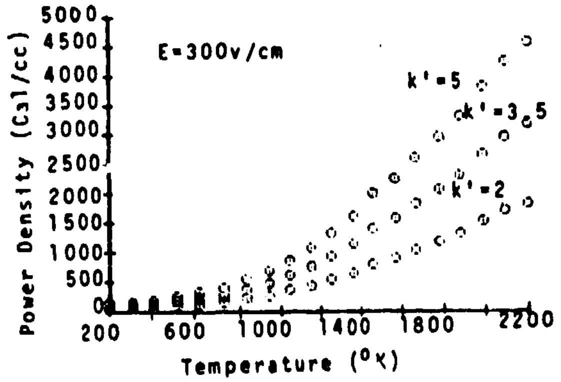

Figure 3. Calculated power density vs temperature coupled into lunar regolith using 2.45 GHz electromagnetic radiation with E=300v/cm and various values of k'.

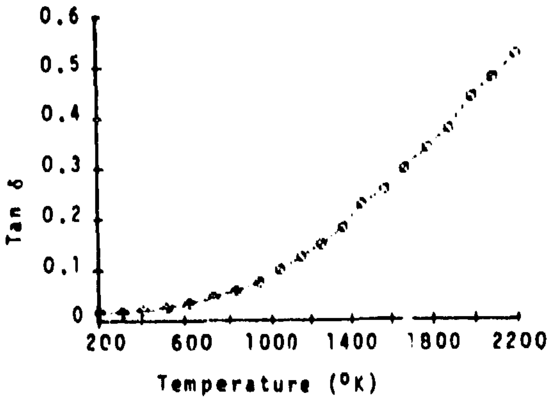

Figure 4. Calculated loss tangent as a function of temperature for lunar regolith.

Next, to calculate the approximate depth of penetration of 2.45 GHz into lunar regolith the expression for skin depth was used:

2) $D=1/\ 2\pi\mu\sigma f$ cm

where D = depth of penetration in cm
μ = magnetic permeability
σ = electrical conductivity
f = frequency

Using this expresssion and conservative values for μ and σ we find that 2.45 GHz radiation will easily penetrate several centimeters into the lunar regolith. For example, a typical value for σ would be 10^{-13} mho-cm and for μ a value of 1 would be typical, since most of the material would only be weakly magnetic at best. Using these values to calculate D yields a depth of penetration of approximately 30 centimeters. Having a knowledge of how deeply microwave heating will peretrate into the regolith is important; however, it is also very important to know the half-power depth of penetration of the electric field into the lunar regolith. This is the depth at which the electric field intensity drops off to half its initial value. The expression which describes this is:

3) $d = 3\lambda o/8.686 \cdot k'\tan\delta$

where d = half-power depth in cm
λo = characteristic wavelength in cm
$\tan\delta$ = loss tangent of regolith
ϵ'/ϵ_o = relative dielectric constant k'.

Using expression (3) the data plotted in Figure 5 were calculated. This figure shows that d decreases with temperature and dielectric constant, however, heating will take place very rapidly at the higher temperatures because of the increase in tan δ and therefore nonuniform heating should not be of great concern. Lastly, expression (4) was used to calculate heating rate in °K/sec.

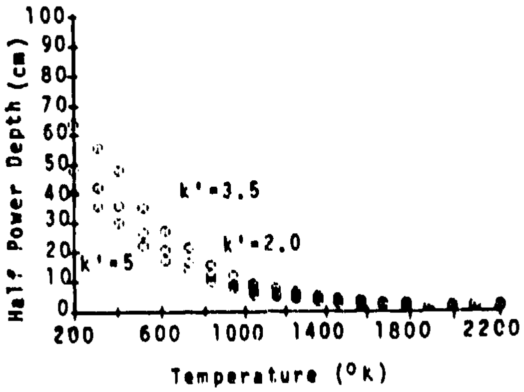

Figure 5. Calculated half power depth of penetration for 2.45 GHz radiation into lunar regolith as a function of temperature and k'.

4) heating rate (R) = $\frac{8\times10^{-12} f E^2 k' \tan\delta}{\rho C_p}$ °K/sec

where ρ = soil density in g/cm^3, C_p = heat capacity of the soil in cal/°K gm and E, f, k' and tan δ are as defined above.

An average value of density of 1.5 g/cc was used and the values of C_p were calculated from Horai et al. [9]. Figures 6-8 give the approximate heating rates as a function of electric field intensity E, dielectric constant and temperature.

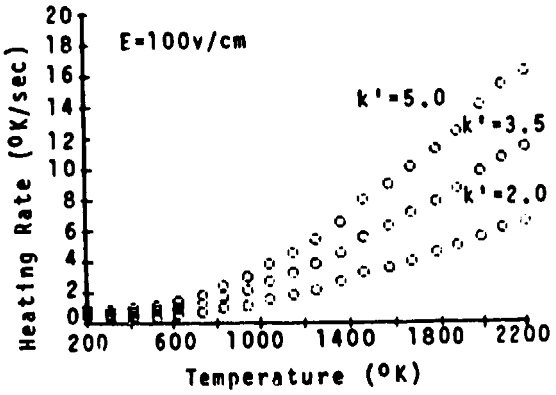

Figure 6. Calculated heating rate vs temperature for lunar regolith when exposed to 2.45 GHz radiation with E=100v/cm.

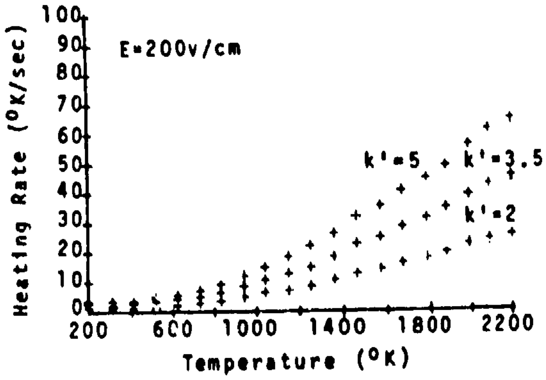

Figure 7. Calculated heating rate vs temperature for lunar regolith when exposed to 2.45 GHz radiation with E=200v/cm.

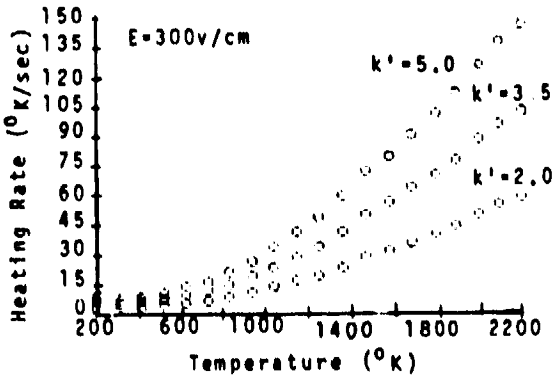

Figure 8. Calculated heating rate vs temperature for lunar regolith when exposed to 2.45 GHz radiation with E=300v/cm.

III. Solar-Electric Power From Lunar Ilmenite

We are in the process of fabricating both terrestrial ilmenite and simulated lunar ilmenite solar cells. Ginley [10] determined the optical band gap of terrestrial ilmenite to be 2.58 eV and its theoretical quantum efficiency to be 15%. This means that any electromagnetic radiation of wavelength shorter than 4651.2 will excite valence electrons into the conduction band. The ilmenite used was a homogeneous polycrystalline sample from Koidu, Sierra Leone, donated by S. Haggerty of the University of Massachusetts had no large hematite intergrowths; hematite exsolution was not observed optically although electron microprobe analysis indicated a significant ferric iron component. The Schottky devices consisted of a thin (approximately 60-80μ) film of aluminum deposited directly on top of the ilmenite and a backside coating of indium-gallium. The front coating of aluminum was chosen to maximize the difference between the work function of the metal on the ilmenite substrate so as to maximize the Schottky barrier. Subsequent characterization of the backside contact has shown it to be rectifying and not ohmic. Figure 9 shows the back to back diode characteristics observed for the lunar simulant ilmenite. Some very small photoresponse was seen, as shown in Figure 10, however, until the backside contact problem is solved an accurate characterization of cell properties cannot be made. Further work to correct this is in progress.

Figure 9. Back to back diode characteristics measured on simulated lunar ilmenite. Top diode is Schottky barrier of interest formed between aluminum and ilmenite, vertical division, 5 μA Horizontal division, .5 V.

Figure 10. Photoconductivity observed in terrestrial ilmenite device. Vertical division, 10 µA Horizontal division, 50 mV.

IV. Discussion

From the generated heating curves it is seen that using electric field strengths of 0.2 to 0.3 Kv/cm at 2.45 GHz should cause sufficiently rapid heating of lunar regolith to make this a practical method for producing fused or sintered products. One could envision a lunar rover pulling a bank of magnetrons housed within parabolic metal reflectors over the lunar surface, heating or sintering the regolith. Figure 11 is a cartoon of such a system with a grader blade to smooth the regolith in front of the trailing magnetrons. The material fused could be left in place as a relatively dust-free roadbed or surfaced area, or cut into blocks or other structural forms. In more advanced concepts, a cold-plate system of collecting liberated volatile elements (H, He) might be coupled to the microwave heating system [11].

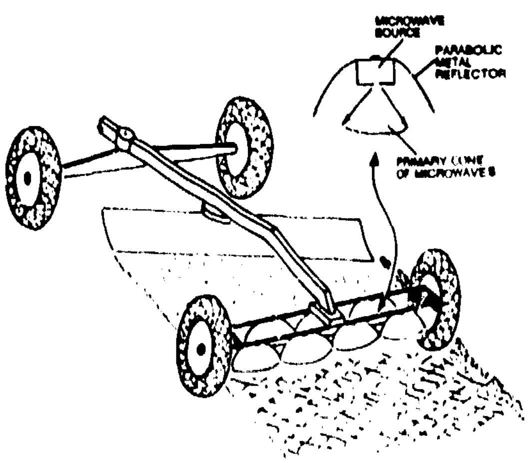

Figure 11. Cartoon of how microwave heating of lunar soil might be achieved.

From the preliminary results of our charac-

it appears that the simulated lunar device has the better cell characteristics because of its high purity. However, until the back contact problem is solved, actual cell efficiency will not be measurable. It is expected that if actual ilmenite photovoltaic devices are fabricated on the Moon, solar cells more sophisticated than these Schotky barrier solar cells will be made since better solar cell efficiencies can be achieved using other approaches. However, a distinct advantage of the Schottky barrier cell is its simplicity and ease of manufacture.

VI. Conclusions

The lunar surface offers many of the resources necessary for the formation of a lunar base. By effectively using all of the energy options available for working on the lunar surface, the flexibility of operations around the lunar base can be maximized. The ideas presented in this paper suggest a low-technology approach both to the manufacture of sintered or fused lunar materials and to the fabrication of photovoltaic devices for power generation.

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